

VAND-TH-94-1

January 1994

Decays of a fermiophobic Higgs

MARCO A. DÍAZ AND THOMAS J. WEILER

Department of Physics and Astronomy
Vanderbilt University, Nashville, TN 37235

Abstract

We explore the phenomenology of a fermiophobic Higgs: a Higgs whose couplings to fermions are suppressed. We calculate the branching ratios of a Higgs decaying to $\gamma\gamma$, W^*W^* , Z^*Z^* , $Zb\bar{b}$, $Z\gamma$, $\gamma b\bar{b}$, and final states involving vector mesons like Υ , J/Ψ and ρ . In order to calculate these branching ratios we perform a complete one-loop renormalization of the vertices $HZ\gamma$ and $H\gamma\gamma$. The decay mode $H \rightarrow \gamma\gamma$ is near unity for a Higgs below the W mass, which provides a clean way of discovering a light fermiophobic Higgs. Interesting modes involving the vector mesons Z , γ , ρ , J/Ψ , and Υ are carefully analyzed.

* Presented by Marco A. Díaz at the Third Annual SAHEP Gulf Shores Meeting, Gulf Shores, Alabama, January 3-5, 1994.

It is perfectly possible that the Higgs mechanism responsible for generating the masses of the gauge bosons is independent from the mechanism that generates the fermion masses. In this way, the existence of a “fermiophobic” Higgs is possible^[1], whose tree level couplings to fermions are zero[★].

Higgs fields in representations other than doublets contribute to gauge boson masses but do not couple directly to fermions. Nevertheless, the ρ parameter restricts the vacuum expectation values of those Higgs fields. But even in models with only Higgs doublets we can find fermiophobia^[3]. For example in two Higgs doublets model of type I, in which only one Higgs doublet (say, Φ_1) couples to fermions, the second Higgs field Φ_2 will have zero couplings to fermions. One way to implement this fermiophobia is imposing the discrete symmetry $\Phi_2 \rightarrow -\Phi_2$. But this fermiophobia will be partial, since the mass eigenstates (H and h) are a mixture of Φ_1 and Φ_2 . If we fine-tune the mixing angle α to $\sin \alpha = 0$ then one of the Higgs mass states (say H) will be fermiophobic at tree level.

The fine-tuning $\sin \alpha = 0$ at tree level does not guarantee perfect fermiophobia. There is a one-loop induced vertex $Hf\bar{f}$. In Fig. 1 we show the one-loop contributions to the vertex $Hf\bar{f}$ in the fermiophobic case. The sum of these graphs is infinite; therefore the vertex $Hf\bar{f}$ is infinitely renormalizable, and we need an experimental measurement in the Higgs sector to fix the counterterm. This arbitrariness leads us to define an extreme fermiophobic Higgs H_F , as that obtained when we set the renormalized vertex $Hf\bar{f}$ to zero. We stress that a more realistic Higgs would be partially fermiophobic, *i.e.* with suppressed but non-zero couplings to fermions.

In order to calculate the different branching ratios of interest, we perform a complete one-loop renormalization of the vertices $H_F Z^* \gamma^*$ and $H_F \gamma^* \gamma^*$ where the superscript $(^*)$ means that the gauge boson may or may not be real^[4,5]. The calculation is simplified if we expand the sum $\Sigma_{HV_1V_2}$ of all Feynman diagrams

★ This kind of Higgs has been also analyzed in ref. [2].

contributing to the vertex HV_1V_2 , $V_i = \gamma$ or Z , in the following form factors:

$$\Sigma_{HV_1V_2}^{\mu\nu}(p^2, k^2, k'^2) = A_{V_1V_2}g^{\mu\nu} + B_{V_1V_2}k^\nu k'^\mu + \dots \quad (1)$$

where p^2 is the momentum squared of the Higgs, and k^μ (k'^ν) is the four-momentum of the vector boson V_1 (V_2). There are three other form factors but they do not contribute to the total widths we calculate. If V_1 or V_2 is a real γ , then gauge invariance imposes the following relation between the two relevant form factors:

$$A_{V\gamma} = -(k \cdot k')B_{V\gamma} \quad (2)$$

There are no tree level vertices $H\gamma\gamma$ or $HZ\gamma$; these are induced at the one-loop level. In Fig. 2 we show the different contributions to the two vertices. There are two kind of diagrams that contribute to the vertex $HZ^*\gamma^*$: the irreducible and the reducible. The latter diagrams involve the mixing between the Z gauge boson and the photon. Both groups of diagrams are infinite and each one needs a counterterm. The mixing between the Goldstone boson G^0 and the photon does not contribute to the form factors A and B . In opposition to the previous case, the sum of the irreducible diagrams contributing to the vertex $H\gamma^*\gamma^*$ is finite and the counterterm is zero. There is no contribution from reducible diagrams to $H\gamma^*\gamma^*$. In Fig. 3 and 4 we display the irreducible diagrams contributing to the two vertices $HZ^*\gamma^*$ and $H\gamma^*\gamma^*$. They can be divided into triangular diagrams (Fig. 3) and non-triangular (Fig. 4), induced by four point vertices involving four gauge bosons or two scalars and two gauge bosons. We neglect charged scalar loop contributions, since scalar loops are much smaller (and model dependent).

The renormalization scheme used in the gauge boson sector is outlined in ref. [6] (see also ref. [7]): the physical masses of the Z and W gauge bosons are given by the pole of each propagator, the tree level $\gamma e\bar{e}$ vertex is fixed by the electric charge measured at $q^2 = 0$, and no mixing between the photon and the Z gauge boson at $q^2 = 0$ is imposed.

For comparison, we start in Fig. 5 showing some branching ratios of the Standard Model Higgs^[8]. We see that the dominant decay mode is $H \rightarrow b\bar{b}$ with a branching ratio equal to unity up to a Higgs mass approximately equal to 150 GeV. Above that mass, $H \rightarrow W^*W^*$ becomes dominant. The $H \rightarrow \gamma\gamma$ branching ratio lies between 10^{-4} and 10^{-3} . In Fig. 6 we plot the branching ratios of the different decay modes of the fermiophobic Higgs. We focus our attention on the following decay modes: W^*W^* , Z^*Z^* , ZZ , $Z\gamma$, $\gamma\gamma$, $Zb\bar{b}$, $\gamma b\bar{b}$, $Z\Upsilon$, $\gamma\Upsilon$, and $\Upsilon b\bar{b}$. We also explore other vector mesons like ρ and J/Ψ . In the modes $Z\gamma$, $\gamma\gamma$, and $\gamma b\bar{b}$, the gauge invariance constraint of eq. (2) is checked algebraically and numerically. In the latter case, it is necessary to include box diagrams in order to maintain gauge invariance. We do so. The decays into two gauge bosons W^*W^* and Z^*Z^* are treated at tree level. In a forthcoming publication^[4] we will include the loop induced $\gamma^*\gamma^*$ and $Z^*\gamma^*$ contributions as well. The virtual gauge boson decays into two fermions and we sum over all possible fermions in the final state. The rest of the decay modes include one loop radiative corrections through the vertices $HZ\gamma$ and $H\gamma\gamma$. For example, in the decay $H_F \rightarrow Zb\bar{b}$ there is a contribution from the tree level vertex HZZ^* with one of the Z bosons being off-shell and decaying into a pair $b\bar{b}$, and a contribution from the one-loop induced vertex $HZ\gamma^*$ with the off-shell photon decaying into $b\bar{b}$.

The decay mode $H_F \rightarrow \gamma\gamma$ is dominant if the Higgs mass is less than about 90 GeV. For Higgs masses above 100 GeV the main decay mode is W^*W^* followed by Z^*Z^* . The ratio between the tree level Z^*Z^* branching ratio and the branching ratio $Zb\bar{b}$ calculated also at tree level (including only the tree level vertex HZZ) is $B(Z \rightarrow b\bar{b}) \approx 0.15$. However, here we compare the tree level Z^*Z^* mode with the one-loop corrected $Zb\bar{b}$ mode. This permits us to appreciate the effect of radiative corrections on the decay $H_F \rightarrow Zb\bar{b}$: the loop-induced $Z\gamma^*$ amplitude exceeds the tree-level ZZ^* amplitude for this case.

We also find that the decay modes involving the vector meson^[9] Υ have branching ratios as high as 10^{-5} . Above 100 GeV the most important Upsilon mode is $Z\Upsilon$ and below that mass, $\gamma\Upsilon$. Other vector mesons are studied in Fig. 7 where

we make a comparison between ρ , J/Ψ and Υ . For the light mesons, the decay $H_F \rightarrow b\bar{b}M$ ($M = \rho$ or J/Ψ) becomes dominant over the ZM modes for large Higgs masses. The $\rho b\bar{b}$ ($J/\Psi b\bar{b}$) mode may be as high as 10^{-2} (10^{-4}). Below 100 GeV the most important mode is γM in the three cases studied ($M = \rho$, J/Ψ or Υ), and for the light meson ρ the branching ratio is about 10^{-3} .

A clean signature is provided when Υ or J/Ψ decays into a pair of charged leptons. As an example, we compare the decay mode $H_F \rightarrow Z^*\Upsilon$ to the background $H_F \rightarrow Z^*Z^*$ in Fig. 8. Although the Upsilon production rate is small, the Υ stands out over the background (in this figure we present tree level calculations only).

In summary, the main discovery channel of a light fermiophobic Higgs ($m_H \lesssim 90$ GeV) is $H_F \rightarrow \gamma\gamma$ with a branching ratio close to the unity. The production mechanism at LEP will be suppressed by the mixing factor $\cos^2\beta = v_F^2/\sum v_i^2$, where v_i is the vev of the i th Higgs and v_F is the particular vev of the fermiophobic Higgs (in opposition to hadron machines, where the gluon-gluon/top-loop production will be suppressed by fermiophobia). Above 90 GeV, decay is dominantly to four fermions/jets, but modes with Z , γ , and vector mesons like Υ , J/Ψ , and ρ are possibly useful. Vector meson branching ratios are larger for lighter mesons. With production of the fermiophobic Higgs at LEP suppressed by the $\cos^2\beta$ factor, the fermiophobic Higgs could be light.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, grant No. DE-FG05-8SER40226.

REFERENCES

1. T.J. Weiler, VIII Vanderbilt International Conference on High Energy Physics, ed. J. Brau and R.S. Panvini, 1987, World Scientific Publications; H. Pois, T.J. Weiler, and T.-C. Yuan, *Phys. Rev. D* **47**, 3886 (1993).
2. A. Stange, W. Marciano, and S. Willenbrock, report number FERMILAB-PUB-93/142-T.
3. V. Barger, N.G. Deshpande, J.L. Hewett, and T.G. Rizzo, report number ANL-HEP-PR-92-102.
4. Marco A. Díaz and Thomas J. Weiler, in preparation.
5. These vertices are renormalized when one photon is on-shell in: A. Barroso, J. Pulido, and J.C. Romão, *Nucl. Phys.* **B267**, 509 (1986), and J.C. Romão and A. Barroso, *Nucl. Phys.* **B272**, 693 (1986).
6. Marco A. Díaz, *Phys. Rev. D* **48**, 2152 (1993).
7. B.A. Kniehl, *Nucl. Phys.* **B376**, 3 (1992).
8. Standard Model branching ratios, including one-loop renormalization, can be found in: D.Yu. Bardin, P.Ch. Christova, and B.M. Vilenisky, report number JINR-P2-91-140.
9. M.N. Doroshenko, V.G. Kartvelishvili, E.G. Chikovani, and Sh.M. Ésakiya, *Sov. J. Nucl. Phys.* **46**, 493 (1987); V. Barger, K. Cheung, and W.-Y. Keung, *Phys. Rev. D* **41**, 1541 (1990).

FIGURE CAPTIONS

- 1) Fynman diagrams contributing to the one-loop renormalization of the vertex $Hf\bar{f}$ in the case of a fermiophobic Higgs H_F . The sum of the diagrams is infinite, and a counterterm is necessary.
- 2) Contributions to the renormalized vertices $HZ\gamma$ and $H\gamma\gamma$. In the latter case, only the vertex corrections contribute, and the vertex counterterm is zero. In the former case, a non-zero vertex counterterm is necessary, as well as the graphs mixing the Z and the photon. Mixing between the Goldston boson G^0 and the photon does not contribute to the relevant form factors $A_{Z\gamma}$ and $B_{Z\gamma}$.
- 3) Irreducible triangular diagrams contributing to the one-loop induced veteces $HZ^*\gamma^*$ and $H\gamma^*\gamma^*$, where the superscript (*) means that the gauge boson may or may not be on-shell. Charged Higgs loops are small, model-dependent, and omitted.
- 4) Irreducible bubble diagrams contributing to the one-loop induced vertices $HZ^*\gamma^*$ and $H\gamma^*\gamma^*$.
- 5) Branching ratios of the Standard Model Higgs.
- 6) Branching ratios of a fermiophobic Higgs. The decay modes W^*W^* and Z^*Z^* are calculated at tree level. All the others include one-loop corrections to the vertices $HZ\gamma$ and $H\gamma\gamma$. The decay mode $\gamma b\bar{b}$ includes also box diagrams in order to ensure gauge invariance. W^* and Z^* decays are summed over all fermion final states.
- 7) Branching ratio involving a vector meson: ZM , $b\bar{b}M$ and γM , where M may be ρ , J/Ψ or Υ .
- 8) Signal for a fermiophobic Higgs decaying into $Z^*\Upsilon$ compared with the Z^*Z^* background (calculated at tree level).

This figure "fig1-1.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9401259v1>

This figure "fig2-1.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9401259v1>

This figure "fig3-1.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9401259v1>

This figure "fig1-2.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9401259v1>

This figure "fig2-2.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9401259v1>

This figure "fig3-2.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9401259v1>

This figure "fig1-3.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9401259v1>

This figure "fig2-3.png" is available in "png" format from:

<http://arXiv.org/ps/hep-ph/9401259v1>